

3.1.4.1 Technical Targets

A variety of feedstocks and processes are being researched and developed for producing hydrogen fuel. Each technology is in a different stage of development, and each offers unique opportunities, benefits, and challenges. Economics favor certain technologies more than others in the near term, but other technologies are expected to become economically viable as the technologies mature and market conditions shift.

Tables 3.1.2 through 3.1.9 list the DOE technical targets for hydrogen production from a variety of feedstocks. Targets for 2010 are R&D milestones for measuring progress, and are not necessarily the targets required for successful commercialization of the technology. Table 3.1.2 lists the DOE technical targets for distributed hydrogen production from natural gas or liquid fuels. Table 3.1.3 includes technical targets for one membrane system for hydrogen separations and purification from fossil or biomass feedstock. Tables 3.1.4 and 3.1.5 list technical targets for hydrogen production from biomass via gasification with steam reforming and via pyrolysis with steam reforming, respectively. Technical targets for photoelectrochemical and photobiological production of hydrogen are shown in Tables 3.1.6 and 3.1.7, respectively. Tables 3.1.8a and 3.1.8b show the technical targets for hydrogen generation by water electrolysis. Table 3.1.9 lists the technical targets for high-temperature thermochemical hydrogen production.

All targets were developed through preliminary hydrogen production analyses and will be refined further as the technology matures and feedstock trade-offs are identified. Additionally, cost targets will be assessed using more consistent economic assumptions, which are now being developed. The targets and timelines for each technology reflect a number of factors, including the expected size of a production unit, the stage of technology development, and the costs and characteristics of the feedstock. The ultimate goal for each technology is to produce hydrogen at a cost that is competitive with gasoline for transportation applications and with other technologies for stationary power generation.

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Table 3.1.2. Technical Targets: Distributed Production of Hydrogen from Natural Gas and Liquid Fuels

Characteristics		Units	Calendar Year		
			2003 Status ¹	2005 Target	2010 Target ²
Reforming	Natural Gas Cost	\$/kg H ₂	0.66	0.62	0.58 ³
	Other Costs	\$/kg H ₂	3.08	1.36	0.24 ⁴
	Primary Energy Efficiency ⁵	%(LHV)	70 ⁶	72	75
Purification	Cost	\$/kg H ₂	0.17	0.11	0.03
	Hydrogen Efficiency ⁷	%(LHV)	75 ⁸	82	90
Compression	Cost	\$/kg H ₂	0.34	0.29	0.24
	Primary Energy Efficiency	%(LHV)	82 ⁹	85	88
Storage and Dispensing	Cost	\$/kg H ₂	0.25 ¹⁰	0.19	0.11
	Primary Energy Efficiency	%(LHV)	100 ¹¹	100	100
Other	Cost ¹²	\$/kg H ₂	0.50	0.42	0.30
	Primary Energy Efficiency	%(LHV)	100	100	100
Total	Cost	\$/kg H ₂	5.00	3.00	1.50
	Primary Energy Efficiency	%(LHV)	62	68	75

¹ Assumes state-of-the-art technology that is feasible but not necessarily available in a complete system today. This assumption is consistent with the automotive fuel cell performance target assumptions.

² Subsystem targets were developed to achieve 75% LHV overall efficiency and \$1.50/kg total cost goals.

³ Assumes energy cost reductions by way of higher efficiency.

⁴ Assumes a 50% equipment cost reduction from the current scenario. These reductions may not be achievable with incremental development of current state-of-the-art technology and will likely require substantial additional technology improvement.

⁵ Reforming efficiency calculation includes all the energy inputs to both the primary feed stream and secondary streams such as fuel for generating process heat and power for running essential equipment.

⁶ Assuming a steam methane reformer operating at 10 atm.

⁷ Hydrogen efficiency is defined as hydrogen output/hydrogen input of the purification process step. Primary energy efficiency is not specified because it is assumed that the purification off-gases (containing CO, CH₄ and unrecovered H₂) are recycled for use in the reforming step.⁸ Assuming a small-scale PSA system operating at reformer outlet pressure.

⁹ Assuming conventional compressors are used from the PSA outlet pressure to 3,600 psi maximum on-site storage pressure and accumulator-type compressors are used from the storage pressure to 5,000 psi on-board storage.

¹⁰ Based on 3,600 psi on-site gas storage.

¹¹ Assuming high-pressure gas storage with no leaks during storage or dispensing.

¹² Includes site preparation and central controls capital costs, operating labor, rent, utilities, and maintenance parts and labor; excludes operator profit.

Notes: Costs are based on a hydrogen refueling station serving 138 vehicles per day (690 kg per day) with on-site production assuming a very high (90%) utilization factor and relatively low capital recovery factor (11%). Much lower utilization factors would be expected during the early years of fuel cell vehicle introduction. Capital equipment costs for the 2005 and 2010 targets assume mature production volumes of 100 units per year. The current status reflects the cost of using current state-of-the-art available technology and assembling it into a single unit. Energy costs assume a natural gas price of \$4/MMBtu (HHV) and power price of \$0.07/kWh. Primary energy efficiency is defined as Hydrogen Output LHV / Energy Input LHV of the process step. Input energy associated with on-site power use assumes a 35% production and transmission efficiency penalty (typical US grid mix).

Table 3.1.3. Technical Targets: Separation Membranes for Hydrogen Production with Palladium Membranes

Characteristics	Units	Calendar Year		
		2003 Status ²	2005 Target	2010 Target
Flux Rate ¹	scfh/ft ²	60	100	200
Cost	\$/ ft ²	\$150-\$200	\$100-\$150	<\$100
Durability	hours ³	<1,000 ⁴	50,000	100,000
Operating Temp	°C	300-600	300-600	300-600
Parasitic Power ⁵	kWh/ 1,000 scfh	3.2	3.0	2.8

¹ Flux at 20 psi hydrogen partial pressure differential and 400 °C.

² Based on membrane shift reactor with syngas.

³ Intervals between membrane replacement.

⁴ Hydrogen membranes have not been demonstrated to date, only laboratory tested.

⁵ These parasitic power requirements are based on the power required to recompress the hydrogen to 200 psi downstream of the membrane due to the pressure drop across the membrane.

Notes: Targets are based on a palladium membrane that is fuel neutral and can be used for hydrogen separation and purification from a variety of fuels. Although these membranes can be used for both separation and purification, the opportunity to develop other novel H₂ separation and purification technologies will not be precluded. Advances in microporous membranes and ion transport membranes, for example, are expected.

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Table 3.1.4. Technical Targets: Central Hydrogen from Biomass via Gasification and Steam Reforming

Characteristics		Units	Calendar Year			
			2003 Status ¹	2005 Target	2010 Target ²	2015 Target
Biomass feed ³	Cost	\$/kg H ₂	0.80	0.70	0.60	0.50
Operations through gasification ⁴	Cost	\$/kg H ₂	1.60	1.50	1.20	1.00
	Energy Efficiency	% (LHV)	68	69	75	82
Reforming ⁵	Cost	\$/kg H ₂	0.50	0.50	0.40	0.20
	Energy Efficiency	% (LHV)	85	86	89	93
Purification ⁶	Cost	\$/kg H ₂	0.40	0.40	0.30	0.30
	Energy Efficiency	% (LHV)	74	74	77	82
Total	Cost ⁷	\$/kg H ₂	3.60	3.30	2.60	2.00
	Net Energy Ratio ⁸		28	29	34	41

¹ Current status of capital cost for gasification section assumed to be 30% greater than those predicted in Spath and Mann (2000) for 2010, according to reductions shown in EPRI, Renewable Energy Technology Characterizations, EPRI TR-109496, December 1997. Incremental improvement through 2005 is assumed. Current reforming costs are assumed to be 50% higher than those in 2010.

² Capital cost for gasification, reforming, and purification sections for 2010 taken from Spath and Mann, 2000.

³ Biomass cost in 2010 = \$42/bone dry ton. Feedstock costs for other years based on relative total process efficiencies.

⁴ Includes biomass handling and drying, gasification, and compression prior to the reformer, plus associated fixed and non-feedstock variable operating costs. Capital costs for gasification are according to reductions shown in EPRI, Renewable Energy Technology Characterizations, EPRI TR-109496, December 1997. Gasification costs in 2020 assume innovative process design, such as integrated gasification/reforming.

⁵ Includes steam reforming reactor, high temperature shift reactor, low temperature shift reactor, and heat exchangers between reactors. Includes associated fixed and non-feedstock variable operating costs. Efficiency includes generation of coproduct steam.

⁶ Assumes commercially available pressure swing adsorption (PSA). Includes associated fixed and nonfeedstock variable operating costs. Source: Spath and Mann, 2000.

⁷ Total cost is for low-pressure (300 psi) hydrogen, at the plant gate.

⁸ Net energy ratio is defined as the amount of energy in the product hydrogen, divided by the fossil energy consumed within the system (including feedstock production and delivery, equipment manufacture, grid electricity production used by the system, and waste disposal). Because biomass is a renewable resource, the energy it contains is not considered to be consumed. Calculations made from Mann and Spath, 1997, Life Cycle Assessment of a Combined Cycle Power System, NREL/TP-430-23076, National Renewable Energy Laboratory.

Costs are for a projected biomass gasification/steam reforming plant, processing 1,046 bone dry Mg/day biomass, with a capacity of 75,000 kg H₂/day.

Research is required to achieve the cost targets (see Section 3 – Technical Challenges, and Section 3.4 – Hydrogen Production from Biomass Technical Barriers).

Table 3.1.5. Technical Targets: Central Hydrogen from Biomass via Pyrolysis and Steam Reforming

Characteristics		Units	Calendar Year			
			2003 Status ¹	2005 Target	2010 Target ²	2015 Target
Biomass feed ³	Cost	\$/kg H ₂	0.80	0.80	0.70	0.60
Operations through pyrolysis ⁴	Cost	\$/kg H ₂	1.90	1.90	1.50	1.20
	Energy Efficiency	% (LHV)	65	66	72	79
Reforming ⁵	Cost	\$/kg H ₂	0.70	0.60	0.40	0.30
	Energy Efficiency	% (LHV)	83	84	87	91
Purification ⁶	Cost	\$/kg H ₂	0.40	0.40	0.30	0.30
	Energy Efficiency	% (LHV)	74	74	77	82
Total	Cost ⁷	\$/kg H ₂	3.80	3.70	2.90	2.40
	Net Energy Ratio ⁸		26	27	32	39

¹ Current status of capital cost for pyrolysis section assumed to be 30% greater than that predicted in Spath and Mann (2000) for 2010, according to reductions shown in EPRI, Renewable Energy Technology Characterizations, EPRI TR-109496, December 1997. Incremental improvement through 2005 is assumed. Current reforming cost is assumed to be 50% higher than that in 2010.

² Capital cost for reforming and purification sections for 2010 taken from Spath and Mann, 2000.

³ Biomass cost in 2010 = \$42/dry ton.

⁴ Includes biomass handling and drying, pyrolysis, and delivery of prepared pyrolysis oil to a central reformer, plus associated fixed and non-feedstock variable operating costs. Capital costs for pyrolysis are based on reductions shown in EPRI, Renewable Energy Technology Characterizations, EPRI TR-109496, December 1997.

⁵ Includes steam reforming reactor, high temperature shift reactor, low temperature shift reactor, and heat exchangers between reactors. Includes associated fixed and non-feedstock variable operating costs. Efficiency includes generation of coproduct steam.

⁶ Assumes commercially available PSA. Includes associated fixed and nonfeedstock variable operating costs. Source: Spath and Mann, 2000.⁷ Total cost is for low-pressure (300 psi) hydrogen, at the plant gate.

⁸ Net energy ratio is defined as the amount of energy in the product hydrogen, divided by the fossil energy consumed within the system (including feedstock production and delivery, equipment manufacture, grid electricity produced for use by the system, and waste disposal). Because biomass is a renewable resource, the energy it contains is not considered to be consumed.

Costs are for a projected biomass pyrolysis/steam reforming operation, processing a combined total of 1,112 bone dry Mg/day biomass, with a capacity of 75,000 kg H₂/day. Several small pyrolysis units are assumed to be located near the source of the biomass residue, providing pyrolysis oil to a central reformer. Primary source is Spath and Mann, 2000, NREL/MP-33112, National Renewable Energy Laboratory. Cost projections assume no coproduct; coproduct opportunities may significantly reduce final cost, while providing market flexibility and heat integration savings.

Research is required to achieve the cost targets (see Section 3.1.4 – Technical Challenges, and Section 3.1.4.2.2 – Hydrogen Production from Biomass Technical Barriers).

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Table 3.1.6. Technical Targets: Photoelectrochemical Hydrogen Production

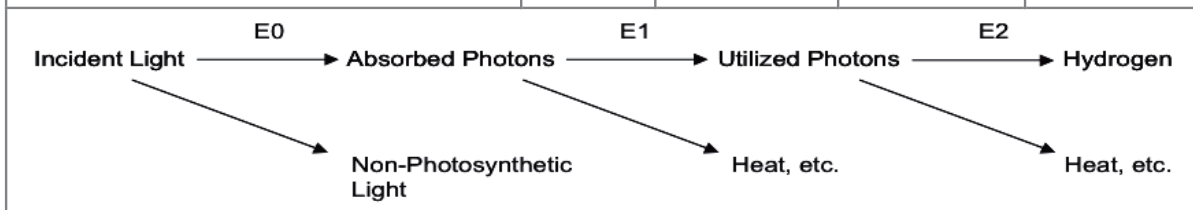
Characteristics	Units	2003 Status	2005 Target	2010 Target	2015 Target
Solar-to-Hydrogen Efficiency	%	7	7.5	9	14
Durability	hours	100	1,000	10,000	20,000
Cost ¹	\$/kg	N/A ²	360	22	5

¹ Costs are for low-pressure hydrogen, at the plant-gate. Primary source is Mann, Spath, and Amos: Technoeconomic Analysis of Different Options for the Production of Hydrogen from Wind, Solar, and Biomass, Proceedings of the 1998 U.S.DOE Hydrogen Program Review, NREL/CP-570-25315. Costs were projected from the reference report by scaling linearly with durability and inversely with efficiency.

² Currently, the highest efficiency systems have the shortest lifetime, and the lower efficiency systems have the longest lifetimes. The optimum system will likely be a compromise between efficiency and lifetime. It is inappropriate to estimate current system cost given the current demonstrated durability results for the higher efficiency materials.

Table 3.1.7. Technical Targets: Photobiological Hydrogen Production

Characteristics	Units	2003 Status	2005 Target ¹	2010 Target ²
Utilization Efficiency of Absorbed Light Energy (E1)	%	~5	10	20
Absorbed Light Energy to Hydrogen Efficiency (E1*E2)	%	0.1	0.5	5
Duration of Continuous Photoproduction ³	hours	240	500	1500
Cost ⁴	\$/kg	200	100	30



E0 reflects light collection efficiency of the photobioreactor and the fact that only a fraction of incident light is photosynthetically active.

E1 is the efficiency with which algae convert the energy of absorbed photons to chemical energy (i.e. electrons).

E2 reflects the efficiency with which this chemical energy is converted to hydrogen.

E1 and E2 represent peak efficiencies.

¹ 2005 target is based on analysis of best technologies available, theoretically integrated into a single organism.

² 2010 target is based on analysis of best technologies available, physically integrated into a single organism.

³ E1 and E2 represent peak efficiencies. Duration reflects continuous production, not necessarily at peak efficiencies.

⁴ Costs are for low-pressure hydrogen, at the plant-gate. Primary source is Amos, Wade: Cost Analysis of Photobiological Hydrogen Production from Chlamydomonas reinhardtii Green Algae, NREL milestone report, September 2000. Cost projections were modified to reflect research advancements toward continuous hydrogen production systems.

Table 3.1.8a. Technical Targets: Water Electrolysis¹

Characteristics		Units	250 kg/day Refueling Station ¹			Small-Scale Refueling ² : 2 kg/day		
			Calendar Year			Calendar Year		
			2003 Status	2005 Target	2010 Target	2003 Status	2005 Target	2010 Target
Power Conversion	Cost ³	\$/kg	0.38	0.28	0.08	0.32	0.21	0.12
	Energy Efficiency	% (LHV)	95	96	98	95	96	98
Cell Stack	Cost	\$/kg	0.64	0.48	0.25	1.37	0.79	0.30
	Energy Efficiency	% (LHV)	72	76	81	65	70	79
Balance of Plant ⁴	Cost	\$/kg	0.13	0.13	0.07	0.21	0.14	0.10
	Energy Efficiency	% (LHV)	98	98	98	97	97	98
Compression ⁵	Cost	\$/kg	0.47	0.32	0.16	0.34	0.21	0.09
	Energy Efficiency	% (LHV)	90	92	95	83	90	93
Storage and Dispensing	Cost ⁶	\$/kg	0.19	0.14	0.06	0.21	0.16	0.12
	Energy Efficiency	% (LHV)	99	99	99	99	99	99
Electricity ⁷	Cost	\$/kg	1.90	1.80	1.60	4.10	3.30	2.80
Total	Cost ⁸	\$/kg	4.70	3.80	2.50	7.40	5.30	3.80
	Energy Efficiency	% (LHV)	60	65	73	49	58	70

¹ Distributed electrolyzer at a refueling station delivering 250 kg of hydrogen per day at 5,000 psig.

² Home/distributed refueling station delivering 2 kg of hydrogen per day at 5,000 psig.

³ Cost reductions reflect possible direct integration with renewable DC electricity or improved power conversion technology.

⁴ Includes hydrogen purification and water removal.

⁵ Compression improvements result from integral electrochemical or other system compression to reduce one or more mechanical compression stages.

⁶ Cost reduction in 2010 based on system optimization to reduce storage costs and possible low cost storage options.

⁷ Off-peak or low-cost renewable energy at \$0.035 per kWh and 40% capacity factor for large system, \$0.06 per kWh and 95% utilization for small home refueling system.

⁸ Based on system capital cost of \$750, \$600, and \$300 per kWe for refueling stations and \$2000, \$1500, and \$800 for small-scale refueling systems per kWe, respectively. Includes O&M, labor and physical plant construction, 15% IRR, 20-year equipment life. Total costs are rounded to the nearest dime.

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Table 3.1.8b. Technical Targets: Centralized Hydrogen Production by Electrolysis¹

Characteristics		Units	2003 Status	2005 Target	2010 Target
Power Conversion	Cost ²	\$/kg	0.10	0.07	0.03
	Energy Efficiency	% (LHV)	95	96	98
Cell Stack	Cost	\$/kg	0.18	0.13	0.06
	Energy Efficiency	% (LHV)	72	76	82
Balance of Plant ³	Cost	\$/kg	0.04	0.04	0.02
	Energy Efficiency	% (LHV)	98	98	99
Electricity ⁴	Cost	\$/kg	2.00	2.00	1.90
Total	Cost ⁵	\$/kg	2.80	2.50	2.00
	Energy Efficiency	% (LHV)	67	72	80

¹ 1000 kg per day electrolyzer producing hydrogen at 100-500 psi at plant gate. (Modular units can be scaled to utility size applications.)

² Cost reductions reflect development in power conditioning/control.

³ Includes purification and water removal.

⁴ Electricity at \$0.045 per kWh and 95% capacity factor (based on nuclear, hydro, or other renewable integrated electricity, steam electrolysis would have lower electricity and include cost for steam).

⁵ Based on system capital cost of \$400, \$300, and \$150 per kWe, respectively. Includes O&M cost, labor, and physical plant construction, 15% discount rate, 20-year equipment life.

Note: Capital costs for steam electrolysis would be higher, electricity costs lower, and efficiency higher. The goal of large scale electrolysis technologies is to reach the \$2.00 per kg cost by 2010 and longer range goal of \$1.50 per kg at the plant gate.

Table 3.1.9. High- and Ultra-High-Temperature Thermochemical Hydrogen Production

Characteristics		Units	2003 Status	2005 Target	2010 Target
High-Temperature Production ¹	Cost at the plant gate	\$/kg	NA ²	10	2
	Energy Efficiency	%	NA ²	25	40
Ultra-High Temperature Solar Production ³	Cost at the plant gate	\$/kg	12	8	4
	Solar concentrator cost	\$/m ²	250	130	75
Process efficiency ⁴		%	20	40	45

¹This is based on large scale central production of hydrogen using waste heat from next generation nuclear energy at 700-900°C using a chemical cycle/water splitting process such as the sulfur-iodide chemical cycle. It is based on plant gate costs at low pressure (~200 psig). Few and only very rough cost estimates of this technology have been done with one published by General Atomics that projects an ultimate possible cost of as low as \$1.00/kg of hydrogen. The targets set for 2005 and 2010 are based on estimates of progress that need to be made to achieve the objective of \$1.00/kg by 2015.

² Nuclear-based thermochemical cycles are an unproven technology with insufficient information for current estimates.

³ Based on estimates for a concentrated solar driven thermal methane splitting process. The cost evaluation is documented in "Assessment of Natural Gas Splitting with a Concentrating Solar Reactor for Hydrogen Production"; April 2002, Pamela Spath and Wade Amos; NREL/TP-510-31949. The values in this Table are based on the work done as part of that report and projecting the required technology improvements from what has currently been achieved at NREL on this process and on solar concentrators. These targets serve as guideposts for ultra-high temperature solar concentrated driven hydrogen production technologies such as possible chemical cycle water splitting processes.

⁴ Defined as the energy to drive the reaction divided by incident direct sunlight on the concentrators.

Note: These technologies are at the early stage of exploration. The targets below are rough guidelines only. The long-term goal (2015) is for the hydrogen produced from these technologies to be cost competitive with gasoline delivered at the refueling station or stationary power facility.

3.1.4.2 Barriers

The following sections detail the technical and economic barriers that must be overcome to attain the Hydrogen Production goal and objectives. The barriers are divided into sections depending on the hydrogen production method.

3.1.4.2.1 Distributed Hydrogen Production from Natural Gas or Liquid Fuels Barriers

A. Fuel Processor Capital Costs. Current small-scale distributed natural gas or liquid fuel reformer technologies are too expensive to supply hydrogen at a cost comparable to that of gasoline. Multiple unit operations and insufficient heat integration contribute to large, costly production and purification subsystems. Improved reforming and shift catalysts are needed to reduce side reactions and improve performance, bearing in mind the availability of the catalyst materials. Shift, separation, and purification step costs need to be reduced by developing new technology such as single-step shift with integrated membrane technology to shift, separate, and purify the hydrogen in one step.

- B. Operation and Maintenance (O&M).** O&M costs for distributed hydrogen production from natural gas or liquid fuels are too high. Systems need to be optimized to reduce labor costs and spare part requirements.
- C. Feedstock and Water Issues.** Distributed hydrogen production relies on local availability of resources, which may pose limitations in certain areas. Technologies and strategies for water clean up are needed to avoid intolerable impurities in reformer steam. Feedstock-flexible reformers are needed to mitigate and/or take advantage of price fluctuations and to address location-specific feedstock supply issues.
- D. Carbon Dioxide Emissions.** Distributed reformers emit greenhouse gases. Cost-effectively sequestering these smaller volume carbon emissions is significantly more challenging than at central hydrogen production facilities that use fossil fuels. This production route should remain limited unless biomass-based liquid fuels are used or until some cost-effective carbon sequestration option for distributed production is discovered.
- E. Control and Safety.** Various control and safety issues are associated with natural gas and liquid fuel reforming, not the least of which is associated with on-off cycling. Effective operations control strategies are needed to minimize cost and emissions, maximize efficiencies, and enhance safety for hydrogen consumers and plant operators.

3.1.4.2.2 Hydrogen Production from Biomass Barriers

- F. Feedstock Cost and Availability.** Hydrogen produced from biomass is not currently cost competitive with gasoline because feedstock and capital costs are too high. Improved feedstock/agriculture technology (higher yields per acre, etc.); lower cost feedstock collection, transportation, and storage options; and improved feedstock preparation are needed (tasks to overcome these barriers will be developed by other agencies and other DOE programs). Because biomass feedstocks are often seasonal in nature, feedstock-flexible processes and/or cost effective feedstock storage are needed to operate year round.
- G. Efficiency of Gasification, Pyrolysis, and Reforming Technology.** Better heat integration, higher gasification pressures, better feedstock handling, improved gas clean up and conditioning (in gasification systems), and improved vapor conditioning (in pyrolysis systems) are needed. Other areas for reforming technology improvements include improved catalysts, heat integration, and reactor configuration for improved yield.
- H. Fermentative Micro-organisms.** Fermentative micro-organisms for hydrogen production have not been adequately evaluated. This area needs to be investigated further.

3.1.4.2.3 Photobiological and Photoelectrochemical Hydrogen Generation Barriers

These technologies are not mature. Several technical barriers must be overcome before economic barriers can be considered. Methods of engineering and manufacturing these systems have not been fully evaluated.

- I. Light Utilization Efficiency.** The micro-organisms used for photobiological hydrogen generation possess large arrays of light-capturing antenna chlorophyll (Chl) molecules. Under bright sunlight, this Chl antenna absorbs much more light than can be utilized

by photosynthetic electron transport, resulting in heat dissipation and loss of up to 80% of the absorbed light. Research is needed to identify ways to increase the light conversion efficiency, including the identification of better and/or modified algae for hydrogen production.

- J. Rate of Hydrogen Production.** The current hydrogen production rate from photosynthetic micro-organisms is far too low for commercial viability. Changes to these organisms, such as the genetic insertion of a proton channel into the thylakoid membrane, are required to overcome the restricting metabolic pathways to significantly increase the rate of hydrogen production.
- K. Continuity of Photoproduction.** Hydrogen-producing algae coproduce oxygen, which inhibits the hydrogen producing enzyme. This inhibition needs to be reduced or eliminated, possibly by separating the oxygen and hydrogen production organism cycles using two separate bioreactors and/or by identifying a less oxygen-sensitive enzyme.
- L. Systems Engineering.** Analysis is needed to identify possible barriers to the cost-effective implementation of photobiological hydrogen generation technologies, such as hydrogen collection systems, continuous bioreactor operation, coproduct opportunities, land area requirements and capital costs.
- M. Material Durability.** Durable materials with the appropriate characteristics for photoelectrochemical hydrogen production that meet the Hydrogen Production program element goals have not been identified. The high-efficiency materials currently available corrode quickly during operation. The most durable materials are very inefficient for hydrogen production.
- N. Materials and System Engineering.** Hybrid designs that combine multiple layers of materials could address issues of durability and efficiency. Techniques for manufacturing appropriate photoelectrochemical materials at commercial scale are needed. Reactor designs using cost-effective, hydrogen-impermeable, transparent materials are also needed to implement photolytic production routes.
- O. Photoelectrochemical Efficiency.** Materials with appropriate bandedge and bandgap for hydrogen production must be developed. Materials with smaller bandgaps more efficiently utilize the solar spectrum, but are often less energetically favorable for hydrogen production because of the bandedge mismatch with respect to either hydrogen or oxygen redox potentials.
- P. Diurnal Operation Limitations.** Photolytic processes lose efficiency because they depend on sunlight, which is unavailable at night and available only at low intensities on cloudy days. This results in increased capital costs for larger facilities to accommodate higher instantaneous production rates and larger hydrogen storage needs. Engineering options need to be carefully analyzed to minimize capital requirements.

3.1.4.2.4 Hydrogen Generation by Water Electrolysis Barriers

- Q. Cost.** The capital costs of electrolysis systems, combined with the high cost and greenhouse gas emissions of electricity from the grid in many locations, are prohibitive to widespread adoption of electrolysis technology for hydrogen production. R&D is needed to develop lower cost materials with improved manufacturing capability to lower capital while improving the efficiency and durability of the system. Systems need to be optimized to minimize O&M costs, including water feed, compression, and cell stack maintenance.

R. System Efficiency. Mechanical high-pressure compression technology exhibits low energy efficiency and often reduces hydrogen purity while adding significantly to the system cost. Large efficiency gains can be realized using electrochemical compression in the cell stack. Low-cost, high-pressure materials need to be developed to provide integral electrochemical or other high-pressure compression technologies to replace some or all mechanical compression stages. Development is needed for low-cost cell stack optimization considering efficiency, electrochemical compression, and durability.

S. Grid Electricity Emissions. The current grid electricity mix in most locations increases greenhouse gas emissions in large-scale electrolysis systems. Low-cost, carbon-free electricity sources are needed.

T. Renewable Integration. More efficient integration with renewable electricity sources is needed to reduce costs and improve performance. Development of small- and large-scale integrated renewable electrolysis systems is needed, including optimization of power conversion and other system components from renewable electricity to provide high-efficiency, low-cost integrated renewable hydrogen production. Novel concepts for carbon-free electrolytic hydrogen production need to be evaluated.

U. Electricity Costs. High-temperature solid oxide electrolysis can use lower cost energy in the form of steam for water splitting to decrease electricity consumption. Technically viable systems for low-cost manufacturing need to be developed for this technology. Electrolysis systems that can produce both hydrogen and electricity need to be evaluated.

3.1.4.2.5 High- and Ultra-High-Temperature Thermochemical Production of Hydrogen Barriers³

This technology is not mature. Several technical barriers must be overcome. Methods of engineering and manufacturing these systems have not been fully evaluated.

V. High- and Ultra-High-Temperature Thermochemical Technology. High-purity hydrogen production from the proposed water-splitting chemical cycles and direct water-splitting technology has not been proven. Thermochemical technology components and subsystems have not been evaluated.

W. High-Temperature Materials. Very high temperatures are employed in these thermochemical systems. Cost-effective, durable materials are needed that can withstand these high temperatures and the thermal cycling duty cycles that are present in the solar concentrator systems.

X. Policy and Public Acceptance. Nuclear restrictions and difficult permitting and licensing procedures severely limit the ability to build nuclear facilities. Permitting and licensing procedures need to be improved, and the public needs to be better educated about the safety issues and potential advantages of nuclear energy systems.

Y. Solar Capital Cost. Solar energy collection is currently expensive and requires large areas of land. Improved, lower-cost solar concentrator/collection technology, including materials, is needed.

³ DOE's Office of Nuclear Energy has the lead responsibility for hydrogen production utilizing nuclear energy for high temperature (700°-1000°C) thermochemical water splitting chemical cycles. The Office of Hydrogen, Fuel Cells, and Infrastructure Technologies will collaborate with Nuclear Energy the high and ultra-high thermochemical hydrogen production R&D activities.

3.1.4.2.6 General (Cross Cutting) Hydrogen Production Barriers

- Z. Catalysts.** Reforming and shift catalysts are not sufficiently durable, efficient, or impurity tolerant. Improved catalysts need to be developed and optimized.
- AA. Oxygen Separation Technology.** Commercial oxygen separation technology relies on expensive and energy-intensive cryogenic separation. Low-cost membrane technology needs to be developed.
- AB. Hydrogen Separation and Purification.** Effective, high flux rate, lower cost, durable hydrogen separation and purification membranes need to be developed. Improved technology for more cost-effective and efficient hydrogen purification is needed. This could include improved PSA technology, the use of membranes to replace PSA technology, and ultimately combining membrane separation and purification with the shift reaction in one unit operation.
- AC. High-Purity Water Availability.** Impacts on water supplies are not understood. Further analysis is needed.
- AD. Market and Delivery.** There is currently no high-volume market for high-purity hydrogen. A feedstock/production strategy and cost-effective delivery systems need to be developed. A market introduction strategy needs to be developed.

3.2.4.1 Technical Targets

Table 3.2.2 lists the technical targets for the Hydrogen Delivery program element. Targets for 2010 are R&D milestones for measuring progress toward the ultimate goal of establishing a hydrogen infrastructure.

The key to achieving the overall cost objectives of the Hydrogen Delivery program element is to bring down the costs and improve the energy efficiency of the key delivery technologies; compression, liquefaction, and pipelines. The targets shown in Table 3.2.2 are based on a preliminary analysis of current technology and costs, estimates of what might be possible with technology advances, initial estimates of total delivery system costs, and the key cost elements that must be reduced to meet the overall cost objectives. Delivery costs are a complex function of the technology, delivery distance, system architecture, and hydrogen demand. Much more analysis needs to be done to better refine the targets listed in Table 3.2.2. This analysis will be the first key task of the delivery program effort.

Preliminary targets are also given for possible hydrogen solid- or liquid-carrier technology that might prove useful for hydrogen delivery. The targets are based on current knowledge about the potential of these technology options for on-board hydrogen storage systems. An analysis of the cost of such systems in a delivery infrastructure have not yet been completed.

Table 3.2.2. Hydrogen Delivery Targets^a

Delivery Method	Target	2003 Status	2005 Target	2010 Target
Gaseous Hydrogen Compression ^b	Cost (\$/kg of hydrogen) Energy Efficiency (%) (LHV)	\$0.18 90%	\$0.17 92%	\$0.14 95%
Hydrogen Liquefaction	Cost (\$/kg of hydrogen) Energy Efficiency (%) (LHV)	\$1.10 65%	\$1.00 70%	\$0.53 87%
Hydrogen Gas Pipelines	Trunk Lines ^c (\$/mile) Distribution Lines ^d (\$/mile)	\$1.4M \$600k	\$1.2M \$500k	\$600k \$350k
Hydrogen Carrier Technology ^e	Hydrogen Content (% by Wt.) Hydrogen Content (kg of hydrogen/M ³) Energy Efficiency (%) (LHV)	3% 45 80%	6.5% 97 82%	10% 150 85%

^aThis table is based on work and analysis performed at NREL and summarized in the report “Costs of Storing and Transporting Hydrogen,” Wade Amos, November 1998, NREL/TP-570-25106. This information was used to arrive at the current (2003) targets and used to project what might be feasible and is necessary to achieve the objectives of the program. Analysis in this area at NREL and on-going research efforts have been factored into this table. Energy efficiencies based on lower heating values (LHVs).

^bBased on compression of hydrogen from 1 atm. to 3,000 psig.

^cBased on the capital requirements for 12 inch lines.

^dBased on the capital requirements for 4 inch lines.

^eThe 2003 values given are based on metal hydride technology. The future targets are based on what is required to achieve the program objectives. These targets might be achieved by a variety of carrier technologies that are being or might be researched.

3.2.4.2 Barriers

A. Lack of Hydrogen/Carrier and Infrastructure Options Analysis. Options and trade-offs for hydrogen/carrier delivery from central and semicentral production to the point of use are not well understood. Distributed production is another option. Analysis is needed to understand the advantages and disadvantages of these various approaches. Many site-specific and regional issues are associated with integrating production and use of hydrogen. Production and delivery systems need to be integrated to minimize cost and take full advantage of local resources and situations.

B. High Costs of Hydrogen Compression. Hydrogen gas has a low volumetric energy density, especially at low pressures. Hydrogen compression is costly and energy intensive. Low-cost, efficient compression technologies are needed.

C. High Costs of Hydrogen Liquefaction. Hydrogen liquefaction is costly and energy intensive. Low-cost, efficient liquefaction technologies are needed.

D. High Capital Cost of Pipelines. Existing hydrogen pipelines are very limited and not adequate to broadly distribute hydrogen. Building new pipelines requires a large capital

investment and may entail costly acquisition of land rights. Development of innovative materials and technologies (seals, components, sensors, and safety and control systems) is needed to reduce cost. Approaches for using existing natural gas pipelines to transport mixtures of natural gas and hydrogen without hydrogen embrittlement and leakage need to be explored, and technologies for separating hydrogen from natural gas need to be developed. The possibility of utilizing or upgrading natural gas pipelines for pure hydrogen use also needs to be examined.

E. Solid and Liquid Hydrogen Carrier Transport. Solid or liquid carriers that can release hydrogen without significant processing operations are possible options for hydrogen transport. Current solid and liquid hydrogen transport technologies have high costs, insufficient energy density, and/or poor hydrogen release and regeneration. Step change improvements in current technologies or new technologies are needed.

F. Transport Storage Costs. Hydrogen storage at production facilities, refueling stations, and other points of end use; surge capacity for pipelines, trucks, and rail at terminals; cryogenic transport and storage; and liquid and gas transport containers for truck and rail are costly. Technologies need to be developed to reduce these costs.

3.3.4.1 Technical Targets

The technical performance targets for hydrogen storage systems are summarized in Table 3.3.2. Figures 3.3.3 and 3.3.4 show the status of current technologies relative to performance and cost targets, respectively. These targets are specifically for on-board vehicle storage systems and were established with the FreedomCAR Hydrogen Storage Technical Team, based on the following vehicle production volume assumptions:

- 2005: very low-volume demonstration
- 2010: suitable for large scale commercial production on a limited number of the least demanding platforms
- 2015: suitable for mass production of a full spectrum of vehicles

Based on the lower heating value (LHV) of hydrogen and a minimum 300-mile vehicle range, the targets are for a complete system, including tank, material, valves, regulators, piping, mounting brackets, insulation, added cooling capacity, and/or other balance-of-plant components. Targets for off-board storage and stationary fuel cell applications will be identified following a study to assess the storage needs for these applications.

Table 3.3.2. Technical Targets: DOE Hydrogen Storage System Targets^{a, b, c}

Storage Parameter	Units	2005	2010	2015
Usable, specific-energy from H ₂ (net useful energy/max system mass) ^d	kWh/kg (kg H ₂ /kg)	1.5 (0.045)	2 (0.06)	3 (0.09)
Usable energy density from H ₂ (net useful energy/max system volume)	kWh/L (kg H ₂ /L)	1.2 (0.036)	1.5 (0.045)	2.7 (0.081)
Storage system cost ^e	\$/kWh net (\$/kg H ₂)	6 (200)	4 (133)	2 (67)
Fuel cost ^f	2001 US\$ gallon gasoline equivalent at pump	3	1.5	1.5
Operating ambient temperature ^g Cycle life (1/4 tank to full) ^h	°C Cycles	-20/50 (sun) 500	-30/50 (sun) 1000	-40/60 (sun) 1500
Cycle life variation ⁱ	% of mean (min) @ % confidence	N/A	90/90	99/90
Minimum and maximum delivery temperature of H ₂ from tank	°C	-20/100	-30/100	-40/100
Minimum full flow	(g/sec)/kW	0.02	0.027	0.033
Minimum delivery pressure of H ₂ from tank (FC=fuel cell, ICE=internal combustion engine)	Atm (abs)	2.5 FC 10 ICE	2.5 FC 35 ICE	2 FC 35 ICE
Transient response 10% to 90% and 90% to 0% ^j	Sec	0.5	0.5	0.5
Start time to full flow at 20°C	Sec	4	0.5	0.5
Start time to full flow at minimum ambient	Sec	8	4	2
Refueling rate ^k	kg H ₂ /min	0.5	1.5	2
Loss of useable hydrogen ^l	(g/hr)/kg H ₂ stored	1	0.1	0.05
Permeation and leakage ^m	Scch/hr	Federal enclosed-area safety-standard		
Toxicity		Meets or exceeds applicable standards		
Safety		Meets or exceeds applicable standards		

^a Based on the lower heating value of hydrogen and a minimum of 300-mile vehicle range; targets are for complete system, including tank, material, valves, regulators, piping, mounting brackets, insulation, added cooling capacity, and/or other balance-of-plant components. System must be energy efficient - for reversible systems, greater than 90% energy efficient; for systems generated off-board, greater than 70% life-cycle efficiency. Useful hydrogen constants: 0.2778kWhr/MJ, ~33.3kWhr/gal gasoline equivalent, lower heating value=32.72 kWh/kg.

^b Unless otherwise indicated, all targets are for both internal combustion engine and for fuel cell use, based on the low likelihood of power-plant specific fuel being commercially viable.

^c Vehicle production volume assumptions: 2005 – very low volume demonstration, 2010 – suitable for large scale commercial production on a limited number of the least demanding platforms, 2015 – suitable for mass production of a full spectrum of vehicles.

^d Generally the 'full' mass (including hydrogen) is used, for systems that gain weight, the highest mass during discharge is used.

^e 2003 US\$; total cost includes any component replacement if needed over 15 years or 150,000 mile life.

^f Includes off-board costs such as liquefaction, compression, regeneration, etc; 2015 target based on H₂ production cost of \$1.50/gasoline gallon equivalent untaxed.

^g Stated ambient temperature plus full solar load

^h Equivalent to 100,000; 200,000; and 300,000 miles respectively.

ⁱ All targets must be achieved at end of life.

^j At operating temperature.

^k 2015 target is equivalent to 3-5 minutes refueling time.

^l Total hydrogen lost from the storage system, including leaked or vented hydrogen; relates to loss of range.

^m Total hydrogen lost into the environment as H₂; relates to hydrogen accumulation in enclosed spaces.

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Figure 3.3.3. Status of current technologies relative to the key performance targets.

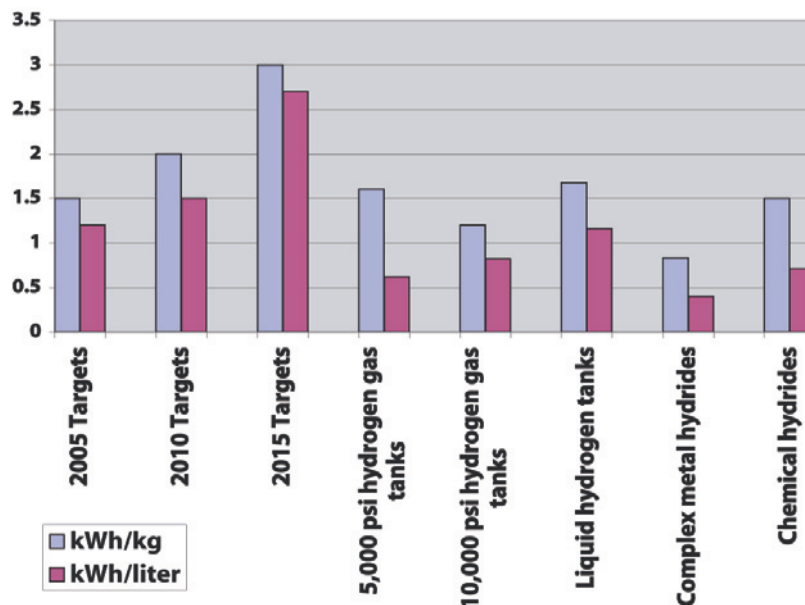
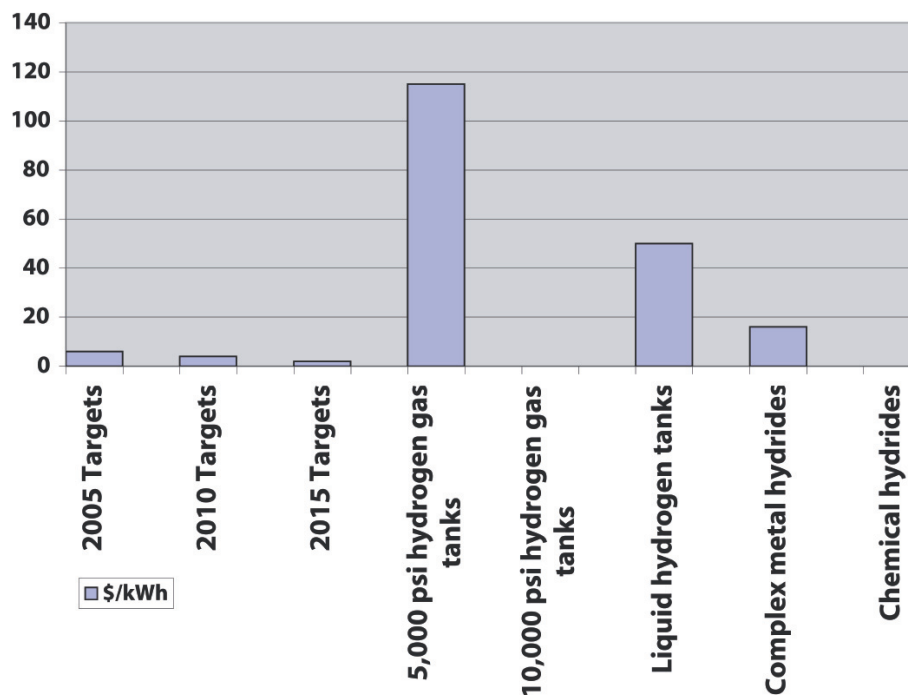


Figure 3.3.4. Status of current technologies relative to the cost targets.



3.3.4.2.1 On-Board Hydrogen Storage Barriers

General

- A. Cost.** The cost of on-board hydrogen storage systems is too high, particularly compared to conventional storage systems for petroleum fuels. Low-cost materials and components for hydrogen storage systems are needed, as well as low-cost, high-volume manufacturing methods.
- B. Weight and Volume.** The weight and volume of hydrogen storage systems are presently too high, resulting in inadequate vehicle range compared to conventional petroleum-fueled vehicles. Materials and components are needed that allow compact, lightweight, hydrogen storage systems while enabling greater than 300-mile range in all light-duty vehicle platforms.
- C. Efficiency.** Energy efficiency is a challenge for all hydrogen storage approaches. For reversible solid-state materials, the energy required to move hydrogen in and out is an issue. Lifecycle energy efficiency is a challenge for chemical hydride storage in which the by-product is regenerated off-board. In addition, the energy associated with compression and liquefaction must be considered for compressed and liquid hydrogen technologies.
- D. Durability.** Durability of hydrogen storage systems is inadequate to meet automobile manufacturer's requirements. Materials and components are needed that allow hydrogen storage systems with a lifetime of 1500 cycles.
- E. Refueling Time.** Refueling times are too long. Hydrogen storage systems with refueling times of three to five minutes, over the lifetime of the system, need to be developed.
- F. Codes and Standards.** Applicable codes and standards for hydrogen storage systems and interface technologies, which will facilitate implementation/commercialization and ensure safety and public acceptance, have not been established. Standardized hardware and operating procedures, and applicable codes and standards, are required.
- G. Life Cycle and Efficiency Analyses.** There are no analyses of the full life cycle cost and efficiency for hydrogen storage systems.

Compressed Gas Systems

- H. Sufficient Fuel Storage for Acceptable Vehicle Range.** Compressed hydrogen storage systems that contain enough hydrogen to provide a range equivalent to conventional vehicles are too bulky, which compromises passenger and luggage space.
- I. Materials.** High-pressure containment limits the choice of construction materials and fabrication techniques, within the weight, volume, performance, and cost constraints. Research into new materials such as metal ceramic composites, improved resins, and engineered fibers is needed.
- J. Lack of Tank Performance Data.** An understanding of the fundamental mechanisms that govern composite tank operating cycle life and failures due to accident or neglect is lacking. Data on tank performance and failure are needed to optimize tank structure for performance and cost. An independent test facility is needed that has the capability to acquire the required data.

K. Balance-of-Plant (BOP) Components. Lightweight, cost-effective, high-pressure BOP components are lacking. These include tubing, fittings, check valves, regulators, filters, relief and shutoff valves, and sensors. Sensors to monitor operating parameters such as temperature and pressure as well as those that monitor the condition of “smart” tanks are needed.

Cryogenic Liquid Systems

L. Hydrogen Boil-Off. The boil-off of liquid hydrogen requires venting and presents an energy penalty and a potential safety hazard, particularly in an enclosed environment. Materials and methods to reduce boil-off in cryogenic tanks are needed.

Reversible Solid-State Material Storage Systems (Regenerated On-Board)

M. Hydrogen Capacity and Reversibility. Hydrogen capacity and reversibility are inadequate at practical operating temperatures and pressures and within refueling time constraints. Adequate cycle life of these systems has not been demonstrated.

N. Lack of Understanding of Hydrogen Physisorption and Chemisorption. Fundamental understanding of hydrogen physisorption and chemisorption processes is lacking. Improved understanding and optimization of absorption/desorption kinetics is needed to optimize hydrogen uptake and release.

O. Test Protocols and Evaluation Facilities. Standard test protocols and independent facilities for evaluation of hydrogen storage materials are lacking.

P. Dispensing Technology. Dispensing technology has not been defined.

Chemical Hydride Storage Systems (Regenerated Off-Board)

Q. Regeneration Processes for Irreversible Systems. Low-cost, energy-efficient regeneration processes for irreversible systems have not been established. Cost-effective regeneration processes need to be identified and developed. Full life cycle analyses need to be performed to understand cost, efficiency, and environmental impacts.

R. By-Product Removal. The refueling process is potentially complicated by byproduct removal. System designs must be developed to address the byproduct issue. Additionally, by-product heat removal will need to be addressed. Excess heat can be produced due to the heat of reaction.

3.3.4.2.2 Off-Board Hydrogen Storage Barriers

S. Cost. Lower cost components and containment methods are needed for hydrogen storage. Lower cost compressors and liquefaction methods, which are being addressed by the Hydrogen Delivery program element (see Section 3.2), are also needed.

T. Efficiency. Energy efficiency is a challenge for compression and liquefaction. More efficient compressor designs and liquefiers are needed (see Section 3.2), as well as novel methods of underground storage to reduce diffusion of hydrogen gas and aboveground storage to reduce venting and boil-off losses.

U. Codes and Standards. Applicable codes and standards are needed to facilitate provision of off-board storage at service stations and upstream in the hydrogen supply chain. Without those codes and standards, production facilities must be sized for larger-than-anticipated demand, resulting in increased cost. Standards for hardware and operating procedures to handle venting and boil-off losses are required.

V. Life Cycle and Efficiency Analyses. Systems analyses are needed to determine the full life cycle cost and efficiency for the entire hydrogen production/delivery system. Such studies should look at the cost and performance of each component in the system.

W. Materials. Like on-board tanks, off-board storage tanks required at service stations and other points upstream in the supply chain will have constraints imposed by high-pressure and/or cryogenic containment. A better understanding of the fundamental mechanisms that govern composite tank operating cycle life is needed. Research into new materials such as metal ceramic composites, improved resins, and engineered fibers is needed.

X. Lack of Underground Storage Performance Data. Bulk underground storage is routinely used to provide seasonal and surge capacity for natural gas and may be required for certain hydrogen production/delivery configurations. Novel approaches are needed to deal with the higher diffusion of hydrogen, as compared to natural gas, and to reduce the cost of storage field development. Options such as alternative cushion gases coupled with membrane-separation of recovered hydrogen and identification of geologic structures with particularly promising permeability characteristics need to be examined. Data on diffusion are needed to optimize structure performance and cost. For underground tank storage, an independent test facility is needed that has the capability to acquire the required data.

Y. Hydrogen Boil-Off. The boil-off of liquid hydrogen requires venting and presents an energy penalty and a potential safety hazard. Materials and methods to reduce boil-off in cryogenic tanks in off-board applications are needed.

3.3.4.2.3 Vehicle Interface Barriers

Technical and cost barriers for vehicle interface technologies will be defined in FY 2004.

3.4.4.1 Technical Targets

Tables 3.4.2 through 3.4.5 list the DOE technical targets for integrated fuel cell power systems running on hydrogen and gasoline (gasoline is a benchmark fuel), and transportation PEM fuel cell stack systems and fuel-flexible fuel processors running on hydrogen-containing fuel from a fuel processor.. Targets for 2010 are R&D milestones for measuring progress, not necessarily the targets required for successful commercialization of the technology.

Table 3.4.6 lists the DOE technical targets for integrated stationary PEMFC power systems operating on natural gas or propane as benchmark fuels. The targets have been developed with input from developers of stationary fuel cell power systems, and have been established for small (3–25 kW) and large (50–250 kW) power levels. The targets assume a sulfur level in the natural gas or propane of less than 6 ppm sulfur (average value).

Tables 3.4.7 and 3.4.8 list the DOE technical targets for consumer electronics, APUs, and truck refrigeration. Tables 3.4.9 and 3.4.10 list DOE technical targets for automotive sensors and compressor/expander units.

Table 3.4.2. Technical Targets: 50-kWe (net) Integrated Fuel Cell Power Systems Operating on Direct Hydrogen^{a□}

All targets must be achieved simultaneously and are consistent with those of FreedomCAR

Characteristics	Units	Calendar year		
		2003 status	2005	2010
Energy efficiency ^b @ 25% of rated power	%	59	60	60
Energy efficiency @ rated power	%	50	50	50
Power density excluding H ₂ storage	W/L	400	500	650
including H ₂ storage	W/L	TBD	150	220
Specific power excluding H ₂ storage	W/kg	400	500	650
including H ₂ storage	W/kg	TBD	250	325
Cost ^c (including H ₂ storage)	\$/kWe	200	125	45
Transient response (time from 10% to 90% of rated power)	sec	3	2	1
Cold start-up time to maximum power @ -20°C ambient temperature	sec	120	60	30
@ +20°C ambient temperature	sec	60	30	15
Emissions		Zero	Zero	Zero
Durability ^d	hours	1000	2000 ^e	5000 ^f
Survivability ^g	°C	-20	-30	-40

^aTargets are based on hydrogen storage in an aerodynamic 2500-lb vehicle and are being updated for compatibility with newly developed hydrogen storage targets.

^bRatio of DC output energy to the lower heating value of the input fuel (hydrogen).

^cIncludes projected cost advantage of high-volume production (500,000 units per year).

^dPerformance targets must be achieved at the end of the durability time period.

^eIncludes thermal cycling.

^fIncludes thermal and realistic drive cycles.

^gAchieve performance targets at 8-hour cold-soak at temperature.

Table 3.4.3. Technical Targets: 50-kWe (net) Integrated Fuel Cell Power Systems Operating on Tier 2 Gasoline Containing 30 ppm Sulfur, Average

(Including fuel processor, stack, ancillaries)

(Excluding gasoline tank and vehicle traction electronics)

All targets must be achieved simultaneously and are consistent with those of FreedomCAR

Characteristics	Units	Calendar year		
		2003 status	2005	2010
Energy efficiency ^a @ 25% of rated power	%	34	40	45
Energy efficiency @ rated power	%	31	33	35
Power density	W/L	140	250	325
Specific power	W/kg	140	250	325
Cost ^b	\$/kWe	300	125	45
Transient response (time from 10 to 90% power)	sec	15	5	1
Cold startup time to rated power @ -20°C ambient temperature @ +20°C ambient temperature	min min	TBD <10	2 1	1 <0.5
Survivability ^c	°C	TBD	-30	-40
Emissions ^d		<Tier 2 Bin 5 ^e	<Tier 2 Bin 5 ^e	<Tier 2 Bin 5 ^e
Durability ^f	hours	1000 ^g	2000 ^h	5000 ⁱ
Greenhouse Gases	One-third reduction compared with conventional SI-IC engines in similar type vehicles			

^aRatio of direct current (dc) output energy to the lower heating value of the input fuel (gasoline).^bIncludes projected cost advantage of high-volume production (500,000 units per year) and includes cost for assembling/integrating the fuel cell system and fuel processor.^cAchieve performance targets at 8-hour cold-soak at temperature.^dEmissions levels will comply with emissions regulations projected to be in place when the technology is available for market introduction.^e0.07 NO_x g/mile and 0.01 PM g/mile.^fPerformance targets must be achieved at the end of the durability time period.^gContinuous operation.^hIncludes thermal cycling.ⁱIncludes thermal and realistic drive cycles.

Table 3.4.4. Technical Targets: Fuel Cell Stack Systems Operating on Hydrogen-Containing Fuel from a Fuel Processor (Gasoline Reformate) in 50-kWe (net) Fuel Cell Systems

(Excludes fuel processing/delivery system)

(Includes fuel cell ancillaries: thermal, water, air management systems)

All targets must be achieved simultaneously and are consistent with those of FreedomCAR

Characteristics	Units	Calendar year		
		2003 status	2005	2010
Stack system power density ^{a,b}	W/L	200	400	550
Stack system specific power	W/kg	200	400	550
Stack system efficiency ^c @ 25% of rated power	%	45	50	55
Stack system efficiency ^c @ rated power	%	40	42	44
Precious metal loading ^d	g/rated kW	<2.0	0.6	0.2
Cost ^e	\$/kWe	200	100	35
Durability ^f	hours	>2000 ^g	>2000 ^h	>5000 ⁱ
Transient response (time for 10% – 90% of rated power)	sec	<3	2	1
Cold startup time to rated power @ –20°C ambient temperature @ +20°C ambient temperature	min min	2 <1	1 0.5	0.5 0.25
Survivability ^j	°C	–40	–30	–40
CO tolerance ^k steady state (with 2% maximum air bleed) transient	ppm ppm	50 100	500 500	500 1000

^a Power refers to net power (i.e., stack power minus auxiliary power requirements).

^b Volume is “box” volume, including dead space, and is defined as the water-displaced volume times 1.5 (packaging factor). Power density includes ancillaries (sensors, controllers, electronics, radiator, compressor, expander, and air, thermal and water management) for stand-alone operation.

^c Ratio of output DC energy to lower heating value of hydrogen-rich fuel stream (includes converter for 300 V bus); ratio of rated power to 25% of rated power efficiencies unchanged, assuming continued proportional reduction in stack efficiency at higher current and proportional increase in compressor efficiency at higher flow rates.

^d Equivalent total precious metal loading (anode + cathode): 0.1 mg/cm² by 2010 at rated power. Precious metal target based on cost target of <\$3/kWe precious metals in MEA [@\$450/roy ounce (\$15/g), <0.2 g/kWe]

^e High-volume production: 500,000 units per year.

^f Performance targets must be achieved at the conclusion of the durability period; durability includes tolerance to CO, H₂S and NH₃ impurities.

^g Continuous operation (pertains to full power spectrum).

^h Includes thermal cycling.

ⁱ Includes thermal and realistic driving cycles.

^j Performance targets must be achieved at the end of 8-hour cold-soak at temperature.

^k CO tolerance requirements assume capability of fuel processor to reduce CO. Targets for the stack CO tolerance are subject to trade-offs between reducing CO in the fuel processor and enhancing CO tolerance in the stack. It is assumed that H₂S is removed in the fuel processor.

Table 3.4.5. Technical Targets: Fuel-Flexible Fuel Processors^a to Generate Hydrogen-Containing Fuel Gas from Reformulated Gasoline Containing 30 ppm Sulfur, Average for 50-kWe (net) Fuel Cell Systems

(Excludes fuel storage; includes controls, shift reactors, CO cleanup, heat exchangers)
All targets must be achieved simultaneously and are consistent with those of FreedomCAR

Characteristics	Units	Calendar year		
		2003 status	2005	2010
Energy efficiency ^b	%	78	78	80
Power density	W/L	700	700	800
Specific power	W/kg	600	700	800
Cost ^c	\$/kWe	65	25	10
Cold startup time to maximum power @ -20°C ambient temperature @ +20°C ambient temperature	min min	TBD <10	2.0 <1	1.0 <0.5
Transient response (time for 10% to 90% power)	sec	15	5	1
Emissions ^d		<Tier 2 Bin 5	<Tier 2 Bin 5	<Tier 2 Bin 5
Durability ^e	hours	2000 ^f	4000 ^g	5000 ^h
Survivability ⁱ	°C	TBD	-30	-40
CO content in product stream ^j steady state Transient	ppm ppm	10 100	10 100	10 100
H ₂ S content in product stream	ppb	<200	<50	<10
NH ₃ content in product stream	ppm	<10	<0.5	<0.1

^aWith catalyst system suitable for use in vehicles.

^bFuel processor efficiency = total fuel cell system efficiency/fuel cell stack system efficiency, where total fuel cell system efficiency accounts for thermal integration. For purposes of testing fuel-processor-only systems, the efficiency can be estimated by measuring the derated heating value efficiency (lower heating value of H₂ × 0.95/ lower heating value of the fuel in) where the derating factor represents parasitic system power losses attributable to the fuel processor.

^cHigh-volume production: 500,000 units per year.

^d0.07 g/mile NO_x and 0.01 g/mile PM (particulate matter).

^eTime between catalyst and major component replacement; performance targets must be achieved at the end of the durability period.

^fContinuous operation.

^gIncludes thermal cycling.

^hIncludes thermal and realistic driving cycles.

ⁱPerformance targets must be achieved at the end of an 8-hour cold-soak at specified temperature.

^jDependent on stack development (CO tolerance) progress.

Table 3.4.6. Technical Targets: Integrated Stationary PEMFC Power Systems Operating on Natural Gas or Propane Containing 6 ppm Sulfur^a, Average

(including fuel processor, stack, and all ancillaries)
All targets must be achieved simultaneously

Characteristics	Units	Small (3–25 kW) Systems			Large (50–250 kW) Systems		
		Calendar Year			Calendar Year		
		2003 Status	2005	2010	2003 Status	2005	2010
Electrical Energy Efficiency ^b @ rated power	%	30	32	35	30	32	40
CHP Energy Efficiency ^c @ rated power	%	70	75	80	70	75	80
Cost ^d	\$/kWe	3000	1500	1000	2500	1250	750
Transient Response (time from 10% to 90% power)	msec	< 3	< 3	< 3	< 3	< 3	< 3
Cold Start-up Time to rated power @ -20°C ambient @ +20°C ambient	min	<15	<10	<5	<20	<15	<10
	min	<10	<5	<1	<10	<5	<2
Survivability (min and max ambient temperature)	°C	-25 +40	-30 +40	-35 +40	-25 +40	-30 +40	-35 +40
Durability @ <10% rated power degradation	hour	>6,000	30,000	40,000	15,000	30,000	40,000
Noise	dB	<70 dBA @ 1 m	<65 dBA @ 1 m	<60 dBA @ 1 m	<65 dBA @ 10 m	<60 dBA @ 10 m	<55 dBA @ 10 m
Emissions Combined NO _x , CO, SO _x , Hydrocarbon, Particulates	g/1000 kWh	<15	<10	<9	<8	<2	<1.5

^a Table assumes average sulfur content in fuels.

^b Ratio of dc output energy to the LHV of the input fuel (natural gas or propane) average value at rated power over life of power plant.

^c Ratio of dc output energy plus recovered thermal energy to the LHV of the input fuel (natural gas or propane) average value at rated power over life of power plant

^d Includes projected cost advantage of high-volume production, entry level production 200 power plants per year, and 2010 production 5000 power plants per year.

Table 3.4.7. Technical Targets: Consumer Electronics (sub-Watt to 50-Watt)^a

Characteristics	Units	Calendar year		
		2003 status	2006	2010
Specific Power	W/kg	unavailable	30	100
Power Density	W/L		30	100
Energy Density	W-h/L		500	1,000
Cost	\$/W		5	3
Lifetime	hours		1,000	5,000
aFew sub-watt to 50-watt fuel cell systems exist and it is premature to specify current status.				

Table 3.4.8. Technical Targets: Auxiliary Power Units (3–5 kW avg., 5–10 kW peak) and Truck Refrigeration Units (10–30kW)

Parameter	Units	2003 ^a status	2006	2010
Specific Power	W/kg	50 ^b	80	150
Power Density	W/L	50 ^b	80	170
Efficiency @ Rated Power ^c	%LHV	20	25	35
Cost	\$/kWe	>2,000	\$1,500	\$400
Cycle Capability (from cold start) over operating lifetime	number of cycles	10	20	500
Durability	hours	100	1,000	5,000 ^d
Start-up Time		2-3 hours	30-45 minutes	15-30 minutes

^a Estimate of current capability based on cell and small stack laboratory developments.

^b Without power conditioning.

^c Durability for light-duty vehicles (LDVs) is 5,000 hours and 15,000 hours for heavy-duty vehicles; the 15,000 hour durability for heavy-duty vehicles (HDVs) is targeted for 2015.

^d Electrical efficiency only—does not include any efficiency aspects of the heating or cooling likely being provided.

Table 3.4.9. Technical Targets: Sensors for Automotive Fuel Cell Systems^a

Sensor	Requirement
Carbon Monoxide	<p>(a) 1–100 ppm reformat pre-stack sensor</p> <ul style="list-style-type: none"> Operational temperature: <150°C Response time: 0.1–1 sec Gas environment: high-humidity reformer/partial oxidation gas: H₂ 30%–75%, CO₂, CO, N₂, H₂O at 1–3 atm total pressure Accuracy: 1%–10% full scale <p>(b) 100–1000 ppm CO sensors</p> <ul style="list-style-type: none"> Operational temperature: 250°C Response time: 0.1–1 sec Gas environment: high-humidity reformer/partial oxidation gas: H₂ 30%–75%, CO₂, CO, N₂, H₂O at 1–3 atm total pressure Accuracy: 1%–10% full scale <p>(c) 0.1–2% CO sensor 250°–800°C</p> <ul style="list-style-type: none"> Operational temperature: 250°–800°C Response time: 0.1–1 sec Gas environment: high-humidity reformer/partial oxidation gas: H₂ 30%–75%, CO₂, CO, N₂, H₂O at 1–3 atm total pressure Accuracy: 1%–10% full scale
Hydrogen in fuel processor output	<ul style="list-style-type: none"> Measurement range: 1%–100% Operating temperature: 70°–150°C Response time: 0.1–1 sec for 90% response to step change Gas environment: 1–3 atm total pressure, 10–30 mol% water, 30%–75% total H₂, CO₂, N₂ Accuracy: 1%–10% full scale
Hydrogen in ambient air (safety sensor)	<ul style="list-style-type: none"> Measurement range: 0.1–10% Temperature range: –30°–80°C Response time: under 1 sec Accuracy: 5% Gas environment: ambient air, 10%–98% RH range Lifetime: 5 years Interference resistant (e.g., hydrocarbons)
Sulfur compounds (H ₂ S, SO ₂ , organic sulfur)	<ul style="list-style-type: none"> Operating temperature: up to 400°C Measurement range: 0.05–0.5 ppm Response time: <1 min at 0.05 ppm Gas environment: H₂, CO, CO₂, hydrocarbons, water vapor
Flow rate of fuel processor output	<ul style="list-style-type: none"> Flow rate range: 30–300 std L/min Temperature: 80°C Gas environment: high-humidity reformer/partial oxidation gas: H₂ 30–75%, CO₂, N₂, H₂O, CO at 1–3 atm total pressure

Ammonia	<ul style="list-style-type: none"> • Operating temperature: 70–150°C • Measurement range: 1–10 ppm • Selectivity: <1 ppm from matrix gases • Lifetime: 5–10 years • Response time: seconds • Gas environment: high-humidity reformer/partial oxidation gas: H₂ 30%–75%, CO₂, N₂, H₂O, CO at 1–3 atm total pressure
Temperature	<ul style="list-style-type: none"> • Operating range: –40°–150°C • Response time: in the –40°–100°C range <0.5 sec with 1.5% accuracy; in the 100°–150°C range, a response time <1 sec with 2% accuracy • Gas environment: high-humidity reformer/partial oxidation gas: H₂ 30%–75%, CO₂, N₂, H₂O, CO at 1–3 atm total pressure • Insensitive to flow velocity
Relative humidity for cathode and anode gas streams	<ul style="list-style-type: none"> • Operating temperature: 30°–110°C • Relative humidity: 20%–100% • Accuracy: 1% • Gas environment: high-humidity reformer/partial oxidation gas: H₂ 30%–75%, CO₂, N₂, H₂O, CO at 1–3 atm
Oxygen in fuel processor and at cathode exit	<p>(a) Oxygen sensors for fuel processor reactor control</p> <ul style="list-style-type: none"> • Operating temperature: 200°–800°C • Measurement range: 0%–20% O₂ • Response time: <0.5 sec • Accuracy: 2% of full scale • Gas environment: high-humidity reformer/partial oxidation gas: H₂ 30%–75%, CO₂, N₂, H₂O, CO at 1–3 atm <p>(b) Oxygen sensors at the cathode exit</p> <ul style="list-style-type: none"> • Measurement range: 0%–50% O₂ • Operating temperature: 30°–110°C • Response time: <0.5 sec • Accuracy: 1% of full scale • Gas environment: H₂, CO₂, N₂, H₂O at 1–3 atm total pressure
Differential pressure in fuel cell stack	<ul style="list-style-type: none"> • Range: 0–1 psi or (0–10 or 1–3 psi, depending on the design of the fuel cell system) • Temperature range: 30°–100°C • Survivability: –40°C • Response time: <1 sec • Accuracy: 1% of full scale • Size: ≤1 in², usable in any orientation • Other: Withstand and measure liquid and gas phases

^aSensors must conform to size, weight, and cost constraints of automotive applications.

Table 3.4.10. Technical Targets: Compressor/Expanders (C/E) for Transportation Fuel Cell Systems^a

Characteristic	Units	2003 Status	2005 Target	2010 Target
Input Power^b at Full Load				
50-kW _e Unit	kW _e	7.0	5.0	5.0
80-kW _e Unit-Reformate/Air	kW _e	–	–	4.7
80-kW _e Unit-Hydrogen/Air with Expander	kW _e	–	–	4.1
80-kW _e Unit-Hydrogen/Air without Expander	kW _e	–	–	13
160-kW _e Unit-Hydrogen/Air with Expander	kW _e	–	–	8.3
160-kW _e Unit-Hydrogen/Air without Expander	kW _e	–	–	26
Efficiency at Full Flow				
50-kW _e Unit-Compressor	%	<70	80	80
50-kW _e Unit-Expander	%	<80	80	80
80-kW _e Unit-Reformate/Air-Compressor	%	–	–	80
80-kW _e Unit-Reformate/Air-Expander	%	–	–	80
80-kW _e Unit-Hydrogen/Air-Compressor	%	–	–	80
80-kW _e Unit-Hydrogen/Air-Expander	%	–	–	80
160-kW _e Unit-Hydrogen/Air-Compressor	%	–	–	80
160-kW _e Unit-Hydrogen/Air-Expander	%	–	–	80
Efficiency @ 20%-25% of Full Flow^c				
50-kW _e Unit-Compressor at 1.3 PR (25%flow)	%	<70	80	80
50-kW _e Unit-Expander at 1.2 PR (25% flow)	%	25-35	45	45
All other 80-160-kW _e units, reformate/air or H ₂ /air				
Compressor at 1.3 PR, (25% flow)	%	–	–	80
Expander at 1.2 PR, (25% flow)	%	–	–	50
Volume^d				
50-kW _e unit	L	10-12	8-11	8-11
All other 80-kW _e units, reformate/air or H ₂ /air	L	–	–	15
All other 160-kW _e units, H ₂ /air	L	–	–	25
Weight^d				
50-kW _e Unit	kg	10-12	8-11	8-11
All other 80-kW _e units, reformate/air or H ₂ /air	kg	–	–	15
All other 160-kW _e units, H ₂ /air	kg	–	–	25
Cost^e				
50-kW _e Unit	\$	600	400	300
80-kW _e units, reformate/air or H ₂ /air	\$	–	–	400
All other 160-kW _e units, H ₂ /air	\$	–	–	600
Turndown Ratio				
50-kW _e Unit		5	10-15	10-15
All other units		–	15	15
Noise dB(A) at 2 meters				
50-kW _e Unit	dB(A)	>90	70	70
All other units	dB(A)	–	–	70

^aTargets represent new, unpublished Revised Guidelines for compressor technologies.

^bInput power to the shaft to power an air system, includes motor/motor controller overall eff. of 85%:

- 50-kWe comp/exp for ref./air flow--76 g/sec (dry) max. flow for compressor, compressor outlet pressure is 2.5 atm. Exp. inlet conditions are 82 g/sec (at full flow), 250°C, and 2.1-2.2 atm.
- No 50-kWe compressor/expander or compressor only unit for hydrogen/air flow only is specified.
- 80-kWe comp/exp unit for ref/air flow--115 g/sec (dry) max. flow for comp., comp. outlet pressure at 2.5 atm. Exp. inlet conditions assumed to be 120 g/sec (full flow), 250°C, and 2.2 atm.
- 80-kWe comp/exp unit for H₂/air flow--87 g/sec (dry) max. flow for comp., outlet pressure is 2.5 atm. Expander (if used) inlet conditions assumed at 87 g/sec (at full flow), 80°C, and 2.3 atm.
- 160-kWe comp/exp for H₂/air flow---175 g/sec (dry) max. flow for comp., comp. outlet pressure is 2.5 atm. Exp. (if used) inlet flow conditions 175 g/sec (full flow), 80°C, and 2.2-2.3 atm.

^cThe pressure ratio is allowed to float as a function of system load/flow rate. The chosen point of operation differs between CEM units due to their different size and point of optimization.

^dWeight, volume, and cost include the motor and motor controller for the 50, 80, and 160-kWe units.

^eCost targets based on a mfg. volume of 100,000 units per year, includes cost of motor and motor controller.

Note: Targets that have not yet been defined are indicated by –.

3.4.4.2 Barriers

Of the many issues discussed here, cost and efficiency present two of the more significant barriers to the achievement of clean, reliable, cost-effective systems.

Transportation Systems Barriers

A. Compressors/Expanders. Automotive-type compressors/expanders that minimize parasitic power consumption and meet packaging and cost requirements are not available. To validate functionality in laboratory testing, current systems often use off-the-shelf compressors that are not specifically designed for fuel cell applications. These result in systems that are heavy, costly, and inefficient. Automotive-type compressors/expanders that meet the FreedomCAR technical guidelines need to be engineered and integrated with the fuel cell and fuel processor so that the overall system meets packaging, cost, and performance requirements.

B. Sensors. Automotive-type sensors are required that meet performance and cost targets for measuring physical conditions and chemical species in fuel cell systems. Current sensors do not perform within the required ambient and process conditions, do not possess the required accuracy and range, and/or are too costly.

C. Thermal Management. Thermal management processes include heat use, cooling, and steam generation. Current heat exchangers do not adequately accommodate the low temperature differential available for fuel cell system heat rejection. Other advanced heat exchangers and materials are required to achieve the most efficient, cost-effective system.

D. Fuel Cell Power System Benchmarking. The interdependency of fuel cell subsystems is an important consideration in the development of individual components for propulsion and APUs. The interdependency of the system components will affect the packaging, response, and efficiency of the power system. Development of a validated system model and periodic benchmarking of integrated fuel cell power systems, subsystems, and components are required to assess technology status. Ultimately, operation of components and subsystems will be validated in the integrated systems developed outside the program.

Distributed Generation Systems Barriers

- E. Durability.** To compete against other distributed power generation systems, stationary fuel cells must achieve greater than 40,000 hours durability. Sulfur-tolerant catalysts and membrane materials are required to achieve this durability target, and research must elucidate failure mechanisms. Benchmarking of the state-of-the-art R&D systems is also necessary.
- F. Heat Utilization.** The low operating temperature of PEM fuel cell system technology limits the use of heat generated by the fuel cell, which represents approximately 50% of the energy supplied by the fuel. More efficient heat recovery systems, improved system designs, and/or higher temperature operation of current systems are needed to utilize the low-grade heat and achieve the most efficient (electrical and thermal) distributed generation power systems.
- G. Power Electronics.** Distributed generation fuel cell power systems will require energy management strategies and power electronics that enable the fuel cell power system to manage power transients and load following requirements efficiently and cost effectively. Grid interconnection may also be a major commercialization issue for many distributed fuel cell power applications as with all emerging distributed power generation technologies (grid interconnection issues are being addressed by the Office of Distributed Energy and Electric Reliability). Priority power management issues include developing a universal dc buss, high-frequency power conditioner, integrated transfer switch and inverter, and grid-independent electronics.
- H. Startup Time.** Fuel cell systems take longer to cold start (30 second minimum) compared to other distributed power generation systems, especially backup power systems. R&D to address startup time through the use of hybrid systems or other viable methods is needed.

Fuel-Flexible Fuel Processors Barriers

- I. Fuel Processor Startup/Transient Operation.** Fuel processors startup slowly and do not respond rapidly to variations in power demand required by automotive and stationary applications. Fuel consumption during this start up period needs to be minimized to compete with conventional ICE technology. Automotive fuel cell power plants will be required to meet rapid startup needs and to follow load variations of typical driving patterns. Improved reactor designs and catalysts with reduced mass are required.
- J. Durability.** Current fuel processing systems have not achieved required durability. A reason for this is the impurities contained in the fuels entering the reformer. Limited data are available on the effects of fuel composition, additives, fuel blends, impurities (e.g., sulfur) and contaminants on fuel processor catalyst and subsystem component durability. The effect of carbon formation on catalyst activity for various fuels and the effect of operating conditions on durability is not adequately defined. On-board sulfur removal technology and impurity tolerant catalysts and/or removal processes are required.
- K. Emissions and Environmental Issues.** Data on the effects of fuel/fuel blend properties on the potential formation of toxic emissions are limited. Fuel processor and stack emissions (including evaporative emissions) are not adequately characterized. Standardized emission test procedures are lacking. Startup emissions are not well characterized.
- L. Hydrogen Purification/Carbon Monoxide Cleanup.** A fuel processor must produce high-quality hydrogen to prevent degradation of the fuel cell stack. Liquid fuels contain

impurities such as sulfur compounds. These compounds and their derivatives, as well as carbon monoxide, must be removed to prevent loss of performance in the fuel cell. To prevent fuel cell catalyst poisoning, the fuel processor needs to deliver a hydrogen stream with CO levels of less than 10 ppm under most operating conditions and a maximum of 100 ppm during transients and startup. Current CO cleanup systems produce a fuel stream with an acceptable CO level under steady-state operation, but require an extensive control system for transient and startup operation. Improved catalysts for preferential oxidation and/or improved membranes for hydrogen separation are needed to meet fuel purity requirements under transient and startup operation.

M. Fuel Processor System Integration and Efficiency. Full-size, fuel-flexible, integrated systems that use improved catalysts and reactors that validate the required operating characteristics and efficiency for automotive applications must be developed. Technical data on the effects of fuel properties on fuel processors are needed. Current understanding of fuel processor subsystem combustion and chemical processes is inadequate. Data and models for fuel impacts on fuel processor performance and emissions are limited. Performance variations for some fuels among various types of fuel processors are not understood.

N. Cost. The cost of fuel processing technology is because the operating temperature requires high-temperature materials, the low activity of shift catalysts requires large reactors, precious metal catalysts must be used, and the complexity of the device requires multiple reactors and thermal integration. Substitution of lower-cost materials (particularly reduced Pt or non-Pt catalysts) and components, and integration of subsystems and functions are required to achieve cost goals.

Component Barriers

O. Stack Material and Manufacturing Cost. Stack material cost/manufacturing (bipolar plates, membrane electrode assemblies, gas diffusion layer) is too high. PEM fuel cell stacks use high-cost bipolar plates, high-cost membranes, and precious metal catalysts (such as Pt). Lower cost, lighter bipolar plates and low-cost, high-performance membranes and catalysts enabling ultra-low loading are required to make fuel cells competitive. Low-cost, high-volume manufacturing processes are also necessary.

P. Durability. Durability of fuel cell stacks, which must include tolerance to impurities and mechanical durability, has not been established. Additional improvements in anode tolerance to carbon monoxide are required to facilitate simplification of the system and to reduce cost and weight. Tolerance to other impurities, such as ammonia and possibly sulfur, is also necessary.

Q. Electrode Performance. Voltage losses at the cathode are too high to meet efficiency targets. Anode and cathode performance depend on precious metal loading, which is currently too high to meet cost targets. In addition, power densities at the higher voltages required for high-efficiency operation are currently too low to meet cost and packaging targets.

R. Thermal and Water Management. Higher temperature membranes (to raise the operating temperature) and/or improved heat utilization, cooling, and humidification techniques are needed. The relatively small difference between the fuel cell stack operating temperature and ambient air temperature is not conducive to conventional heat rejection approaches. Water management techniques to address humidification requirements and maintain water balance are required.

3.5.4.1 Technical Targets

The Technology Validation program element does not develop new component technologies, and therefore does not have technology targets. Instead, this program element will validate whether the technical targets for the individual components (developed within the other subprograms) can still be met when integrated into a complex system and review the future requirements for each component in such integrated systems. Specifically, once technical targets for each individual component have been verified under laboratory conditions, they will be verified under real-life conditions, during the phased demonstration of vehicle and infrastructure systems as part of the systems integration effort.

3.5.4.2 Barriers

In addition to the technical barriers being addressed through RD&D in the other subprograms, there are obstacles to successful implementation of fuel cells and the corresponding hydrogen infrastructure that can only be addressed by integrating the components into complete systems. After a technology has validated achievement of its technical targets in the laboratory, the next step is to show that it can work as designed within complete systems, e.g., FCVs and hydrogen refueling infrastructure. To have confidence in these technologies, they must also be evaluated in multiple systems to acquire sufficient data to validate statistical significance. A by-product of this approach to technology validation is that technical and system problems are revealed and component requirements can be better evaluated. The following barriers will be addressed by the Technology Validation program element to pave the way for commercialization of fuel cell and hydrogen infrastructure technologies.

- A. Vehicles.** In the public domain, statistical data for vehicles that are operated under controlled, real-world conditions is very limited (data such as FCV system fuel economy, thermal management integration (cold start efficiency), durability (stack degradation), and system durability). Most or all the information is proprietary. Vehicle drivability, operation, and survivability in extreme climates, and emissions (hydrogen ICE) are also barriers to commercialization. The interdependency of fuel cell subsystems is an important element that must be considered when developing individual subsystems. Development and testing of complete integrated fuel cell power systems is required to benchmark and validate for optimal component development.
- B. Storage.** Statistical cost, durability, fast-fill, discharge performance, and structural integrity data of hydrogen storage systems that are garnered from user sites need to be provided for the community to proceed with technology commercialization. Current technology does not provide 300+ mile range without interfering with luggage or passenger compartment spaces, nor does it provide reasonable cost and volume for stationary applications. An understanding of composite tank operating cycle life and failure due to accident or neglect is lacking. Adequate cycle life of chemical and metal hydride storage systems need to be evaluated in real-world circumstances.
- C. Hydrogen Refueling Infrastructure.** The high cost of hydrogen production, low availability of the hydrogen production systems, and the challenge of providing safe systems including low-cost, durable sensors are early penetration barriers. Shorter refueling times need to be validated for all the storage concepts. Integrated facilities with footprints small

enough to be deployed into established refueling infrastructures need to be conceptualized and implemented. The impact of greenhouse gas emissions in tank-to-wheels scenarios is not well understood. Interface technology to fast-fill tanks requires reliable demonstrations. Small factory-manufactured, skid-mounted refueling systems need to be proven reliable options in low-volume production systems, for sparsely populated areas with low anticipated vehicle traffic.

- D. Maintenance and Training Facilities.** Lack of facilities for maintaining hydrogen vehicles, personnel not trained in handling and maintenance of hydrogen system components, limited certified procedures for fuel cells and safety, and lack of training manuals are all barriers that must be overcome. Lack of real-world data in the public domain on refueling requirements, operations and maintenance (O&M) of FCVs, and lack of data on greenhouse gas emissions are additional barriers.
- E. Codes and Standards.** Lack of adopted codes and standards that will permit the deployment of refueling stations in a cost-effective and timely manner must be addressed. These are necessary to ensure safety and to determine supplier design goals. Competing international standards prevent U.S. companies from introducing hydrogen technologies. A database also needs to be assembled to ensure that future energy systems based on these technologies can be efficiently installed and operated.
- F. Centralized Hydrogen Production from Fossil Resources.** There are few data on the cost, efficiencies, and availabilities of integrated coal-to-hydrogen/power plants with sequestration options. Hydrogen delivery systems from such centralized production systems need to be validated and operated. Hydrogen separation at high temperature and high pressure and their integrated impact on the hydrogen delivery system needs to be defined.
- G. Hydrogen from Nuclear Power.** Data on the chemical reactions at high temperatures, reaction rates, nonequilibrium reactions, and material properties that can contain highly reactive gases at high pressure for the high-temperature production of hydrogen through thermochemical and electrochemical processes are limited. The cost and O&M of such an integrated system needs to be assessed before high-temperature nuclear reactors are designed and developed for the hydrogen production. Hydrogen delivery options need to be determined and assessed as part of the system demonstration. Validation of integrated systems is required to optimize component development.
- H. Hydrogen from Renewable Resources.** There is little operational, durability, and efficiency information for integrated renewable/electrolyzer systems operating with large renewable facilities to produce hydrogen. Biomass systems operating on low-cost biomass fuels need to validate biomass feed systems, catalyst lifetimes, product co production, and availability on large systems. The integration of biomass and other renewable electrolyzer systems needs to be evaluated.
- I. Hydrogen and Electricity Coproduction.** Cost and durability of hydrogen fuel cell and reformer systems for coproducing hydrogen and electricity need to be statistically validated at user sites. Permitting, codes and standards, and safety procedures need to be established for hydrogen fuel cells located in or around buildings and refueling facilities. These systems have no commercial availability, operational, and maintenance experience.

customers and are based on voluntary involvement of interested parties. The process by which a standard is developed by ISO is outlined below:

- The need for an international standard is expressed by an industry sector, which communicates this need to a national member body.
- The national member proposes the new work item or items to ISO as a body.
- Once recognized by ISO, a formal approval process by the main body and the phases of development are undertaken:
 - o **Definition:** The technical scope of the future standard is identified and defined by working groups of experts from interested countries.
 - o **Consensus:** Countries negotiate the detailed specifications within the standard.
 - o **Approval:** The acceptance by two-thirds of the ISO members that have participated in the standards process, and approved by 75% of all members that vote.

To date, ISO's work has resulted in more than 12,000 international standards. The following ISO Technical Committees are working on standards related to hydrogen and fuel cells:

- **TC 22 - Road Vehicles:** compatibility, interchangeability, and safety, with particular attention to terminology and test procedures for mopeds, motorcycles, motor vehicles, trailers, semi-trailers, light trailers, combination vehicles, and articulated vehicles. The Electric Road Vehicle Subcommittee is addressing operation of the vehicles, safety, and energy storage. France chairs the Technical Committee and Germany chairs the Subcommittee.
- **TC 197 - Hydrogen Technologies:** systems and devices for the production, storage, transport, measurement, and use of hydrogen. Ten working groups are focusing on fuel tanks, multimodal transport of liquid hydrogen, airport refueling facility, hydrogen safety, hydrogen and hydrogen blends, water electrolysis, fuel processing, and transportable gas storage devices.
- **TC 58 - Gas Cylinders:** fittings and characteristics related to the use and manufacture of high-pressure gas storage. One working group on gas compatibility and materials coordinates with TC 197.

International Electrochemical Commission

The IEC is the leading global organization for preparing and publishing international standards for all electrical, electronic, and related technologies. Its charter includes all electrotechnologies including electronics, magnetics and electromagnetics, electroacoustics, multimedia, telecommunication, and energy production and distribution as well as general disciplines such as measurement and performance, dependability, design and development, safety, and the environment.

The IEC is developing standards for the electrical interface to fuel cells. IEC Technical Committee 105 is primarily addressing stationary fuel cell power plants, but has also addressed portable and propulsion fuel cells. There are seven working groups in TC 105: Terminology, Fuel Cell Modules, Stationary Safety, Performance, Installation, Propulsion, and Safety and Performance of Portable Fuel Cells. ANSI coordinates the U.S. position on ISO and IEC standards.

California, which recently adopted the NFPA codes over the ICC codes, although ICC codes have recently included hydrogen into its model building codes.

International standards developed by ISO and IEC will have an increasing impact on U.S. fuel cell interests, especially in portable and propulsion applications. The U.S. appears to be leading the development of fuel cell-related standards, but Japan and Germany have accelerated their efforts in this area. There is increasing pressure for acceptance and reliance on the development of international standards, a position supported by DOE.

As participation in the codes and standards process increases, disagreement about who is responsible for fuel cell vehicle standards has intensified. The IEC has an approved work program that includes standards for the fuel cell module. Other standards committees within the ISO are responsible for road vehicles, hydrogen, and the interface between vehicle and dispenser. Competition, duplication, and conflict must be addressed.

The SAE is assuming more autonomy in the development of standards for vehicular applications. As a national organization, its principal interests should lie with the U.S. industry to accelerate the development and adoption of national standards; however, SAE believes that most of its efforts should be focused on the development of international standards. This has led to some conflict between the various parties because it appears that the U.S. auto companies are not supporting the national agenda, as they have not provided technical experts for new working committees.

Perhaps a more serious challenge is the lack of available data necessary to develop and validate standards. This is due to a number of factors, including concerns about proprietary or competition-sensitive information, rapid technology development, and declining investment income and industry consolidation.

3.6.4.1 Targets

Since it is a voluntary, industry-led process, the federal government can influence but cannot direct the development of the model codes or domestic and international standards. The Codes and Standards program element activities will focus on assisting the commercial acceptance of hydrogen and fuel cell technologies.

By working with states and local code officials, the Hydrogen, Fuel Cells & Infrastructure Technologies Program will help develop training programs that will: 1) explain the new technologies, 2) provide case studies of installations and operation, and 3) communicate the changes in the codes as they pertain to the new technology. It will also work with state and local government officials to assist in the adoption of the approved model codes by conducting workshops and road shows to explain the status of the code process.

Through activities with NFPA and the ICC, the Hydrogen, Fuel Cells & Infrastructure Technologies Program will provide experts and technical data on hydrogen and fuel cell technologies and will facilitate the development of amended model codes for inclusion in their respective family of codes, see Table 3.6.4. Additionally, the program will provide support for industry and laboratory experts to attend and participate in critical international standards development meetings and workshops.

Table 3.6.4. Family of Model Codes

Model Code	Content
Fire Code	Regulations affecting or relating to structures, processes, premises, and safeguards regarding fire and explosions.
Building Code	Ensures public health, safety, and welfare as they are affected by repair, alteration, change of occupancy, addition, and location of existing buildings.
Electrical Code	Ensures public safety, health, and general welfare through proper electrical installation, including alterations, repairs, replacement, equipment, appliances, fixtures, and appurtenances.
Property Maintenance Code	Ensures adequate safety and health as they are affected by existing building structures and premises.
Zoning Code	Enforces land use restrictions and implements land use plan.
Energy Conservation Code	Ensures adequate practices for appliances, HVAC, insulation, and windows for low cost operation.
Residential Code	Applies to the construction, alteration, movement, enlargement, replacement, repair, use, and occupancy of one- and two-family dwellings.
Plumbing Code	Regulates the erection, installation, alternation, repairs, relocation, and replacement, in addition to use or maintenance, of plumbing systems.
Mechanical Code	Regulates the design, installation, maintenance, alteration, and inspection of mechanical systems that are permanently installed and used to control environmental conditions and related processes.
Fuel Gas Code	Regulates the design, installation, maintenance, alteration, and inspection of fuel gas piping systems, fuel gas utilization equipment, and related accessories.
Performance Code	Establishes requirements to provide acceptable levels of safety for fire fighters.

The Program will continue to work directly with the SDOs, by providing supporting technical and coordination meetings to facilitate an accelerated identification and development of new standards for hydrogen storage and production systems; fuel cell performance, maintenance, and reliability; and system monitoring and safety. Table 3.6.5 lists the standards that the SDOs have identified as being required. Finalize a licensing agreement with the SDOs to allow the government to distribute published codes and standards to jurisdictions for the adoption process.

Table 3.6.5. High Priority Standards for Development

Standard	Content
Piping	Hydrogen-specific piping design, installation, training, and certification. Replaces B31.3 reference in ICC Family of Codes.
Storage	Hydrogen storage tank for portable and stationary service. Standard will be independent of adsorbent. New standard for vehicular transport of high-pressure hydrogen to pressures of 10,000 psi. Includes supporting R&D program funded by DOE.
Materials Guide	Ensures public safety, health, and general welfare through proper selection of materials for hydrogen service. Reference for existing design and installation standards.
Hydrogen Quality	Ensures safety by defining testing methods to determine the quality of the fuel independent of production technique.
Mass Flow Measurement	Defines methods to quantify hydrogen mass flow rate to determine appliance efficiency.
Transport	Reviews and modifies existing piping standards and underground storage.

Finally, the Hydrogen, Fuel Cells & Infrastructure Technologies Program will continue to support focused research, testing, and certification for hydrogen components and equipment. An R&D plan will be developed to lay out the requirements for these activities and obtain industry acceptance as needed to provide critical technical and performance data for hydrogen and fuel cell systems.

One critical item that will be addressed through these activities will be the issue of setback distances associated with NFPA 55. Current setback distances for hydrogen storage facilities would make it difficult to place hydrogen refueling stations near roadways. Reduced footprints, which are accomplished by smaller separation distances, are important to commercialization efforts. The resulting technical data will be incorporated into the codes and standards development process.

The targets for this program element are summarized in Table 3.6.6.

Table 3.6.6 Targets for Hydrogen Codes and Standards

- 1) Establish a comprehensive training program for code officials and fire marshals. (Objective 1, Task 1)
- 2) Adopt model building code. (Objective 1, Task 2)
- 3) Negotiate DOE licenses for critical standards and model codes. (Objective 1, Task 7)
- 4) Publish ISO standards. (Objective 2, Task 3)
- 5) Complete and sign memorandum. (Objective 2, Task 4)
- 6) Secure initial license for ISO standards. (Objective 2, Task 5)
- 7) Incorporate new analysis and data into revised standard. (Objective 2, Task 6)
- 8) Implement research program for underground hydrogen storage. (Objective 3, Task 1)
- 9) Agrees in principle, as a nation, to adopt a global technical regulation for hydrogen fuel cell vehicles under GRPE. (Objective 4, Task 9)

3.6.4.2 Barriers

The barriers are summarized below.

- A. Limited Government Influence on Model Codes.** The code development process is voluntary, so the government can affect its progression, but buy-in is ultimately required from code publishing groups.
- B. Competition between ICC and NFPA.** The competition between the ICC and the NFPA, stemming from a number of failed attempts to develop a single fire code, will complicate the creation of consistent hydrogen building codes.
- C. Limited State Funds for New Codes.** Budgetary shortfalls in many states are having a large impact on the adoption of codes and standards, since local jurisdictions do not have the funds for purchasing new codes or for training building and fire officials.
- D. Large Number of Local Government Jurisdictions (approximately 44,000).** Ultimately it is the responsibility of local government jurisdictions to adopt model codes, but budgetary shortfalls in many states and communities will have having a large impact on the adoption of codes and standards, since local jurisdictions do not have the funds for purchasing new codes or for training building and fire officials.
- E. Officials Training Differences.** The training of code officials is not mandated and varies significantly. .
- F. Limited DOE Role in the Development of ISO Standards.** Governments can participate and influence the development of codes and standards, but they cannot direct the development of ISO standards.
- G. Inadequate Representation by Government and Industry at International Forums.** It is expensive to provide adequate representation at international forums and meetings. As a result, there are also difficulties in promoting the findings of international technical committees to domestic industry experts.

- H. International Competitiveness.** International code development is usually complicated and difficult to achieve because of international competitiveness and licensing issues.
- I. Strategic Conflicts between Domestic and International Standards Objectives.** National agendas often create conflicts about the most appropriate domestic and international standards.
- J. Consensus National Agenda on Codes and Standards.** Competitive strategic issues must be overcome in reaching consensus.
- K. Lack of Domestic Industry Support at International Technical Committees.** Domestic hydrogen experts are needed to support the activities conducted within the international technical committees. A great deal of U.S. expertise is employed in small businesses, academia, and government agencies, and the costs and participation requirements are prohibitive.
- L. Competitiveness in Copyright of Published Standards.** The development and licensing of codes and standards is “big” business, and the competitiveness associated with the adoption of one set of codes and standards versus another is usually quite fierce.
- M. NFPA 55 has not yet been completed, but is currently in progress.** NFPA codes are accepted by some states and local jurisdictions; others accept ICC codes. Currently, only the ICC families of codes address the use of hydrogen in the built environment. Jurisdictions that adhere to NFPA codes cannot reference codes that address the use of hydrogen technologies.
- N. Lack of Technical Data to Revise NFPA 55 Standard (for underground and aboveground storage).** Research activities are underway to develop and verify the technical data needed to support codes and standards development, but it is not yet completed. A sustained effort may be required.
- O. Insurance Companies Recognize Current Standards. Insurance rates are tied to codes and standards.** New technologies not yet recognized in codes and standards will have difficulty in obtaining reasonable insurance, and may not be approved in some cases.
- P. Current Large Footprint Requirements for Hydrogen Fueling Stations.** The set back and other safety requirements in effect for the use of hydrogen in industrial applications result in excessively large footprints. There is a need to review all the existing technical data and conduct research, testing, and analysis to ensure that public safety needs are addressed, but that the safety requirements are not so excessive as to prohibit commercialization.

3.7.5.1 Targets

Table 3.7.2 summarizes the technical objectives associated with the Safety program element.

Table 3.7.2. Targets for Hydrogen Safety

- 1) Release historical dossier on safety. (Objective 1, Task 1)
- 2) Incorporate safety protocols into solicitations. (Objective 1, Task 2)
- 3) Conduct first meeting of Hydrogen Safety Review Panel. (Objective 1, Task 3)
- 4) Draft R&D plan for safety related tests and evaluations. (Objective 1, Task 4)
- 5) Implement R&D needs for safety into the spend plan, procurement plan, and budget. (Objective 1, Task 4)
- 6) Accept terms and conditions by the Procurement Office. (Objective 2, Task 5)
- 7) Incorporate selection criteria into all future procurements. (Objective 2, Task 6)
- 8) Incorporate safety criteria into the annual review process in each review area. (Objective 2, Task 7)
- 9) Obtain the first “hit” on public access Database on Safety. (Objective 3, Task 8)
- 10) Complete first 10 safety assessments. (Objective 3, Task 9)
- 11) Receive acceptance by Peer Review Team on the Handbook of Best Management Practices. (Objective 3, Task 10)

3.7.5.2 Barriers

This section details the barriers that must be overcome to achieve the goals and objectives of the Safety program element.

- A. Limited Historical Database for Components.** Only a small number of hydrogen technologies, systems and components are in operation. As such, only limited data are available on the operational and safety aspects of these technologies, and the materials from which they are fabricated.

- B. Access to Industry Proprietary Data.** Hydrogen technologies, systems, and components are still in the pre-commercial development phase. As such, only limited data are available on the operational and safety aspects of these technologies. Sharing safety data is required for projects funded under the Hydrogen, Fuel Cells & Infrastructure Technologies Program.
- C. Validation of Historical Data.** The historical data used in accessing safety parameters for the production, storage, transport, and utilization of hydrogen are several decades old. Validation of these data and an assessment of their use may prove useful in the development of a hydrogen infrastructure.
- D. Technical and Scientific Understanding of Systems Limits the Value of Protocols.** There is a need to better understand the fundamental limits of hydrogen systems.
- E. Obtaining Industry Input and Consensus.** Because of the status of hydrogen technologies and the competitive nature of this industry, individuals and their companies are unwilling to share information or develop consensus opinions on safety. Therefore, sharing information upon request by the Safety Review Panel will be a contractual obligation for participation in the Hydrogen, Fuel Cells & Infrastructure Technologies Program.
- F. Liability Issues.** Lawsuits and insurability are serious concerns that could affect the commercialization of hydrogen technologies.
- G. Lack of Understanding among Procurement Officials.** DOE procurement officials have little understanding of hydrogen safety issues, but will need to include these parameters into solicitations.
- H. General Counsel Acceptance of Procurement Requirements.** DOE General Counsel will need to accept the recommended procurement requirements.
- I. Variation in Standard Practice of Safety Assessments for Components and Energy Systems.** Variations in safety practices and risk assessments are inevitable and could result in accidents.
- J. Continued Project Follow-On is Not Prevailing Safety Practice.** Safety practices will need to be maintained throughout the duration of the projects, which is not the prevailing approach.
- K. Existing Data are Proprietary or Not Easily Accessible.** In many cases, critical safety data and information are not shared because they are proprietary or not readily accessible.
- L. Expense of Data Collection and Maintenance.** Developers may choose not to pursue the detailed collection and maintenance of all safety data and information because of the added expense.
- M. Quality of Data.** In cases where safety data are routinely or semi-routinely collected, the quality of the data may not meet the exacting collection standards needed to communicate safety assurance.

N. Lack of Mandatory Reporting Requirements for Past Hydrogen Incidents.

There are currently no mandatory reporting requirements for hydrogen safety incidents; consequently, there is little specific information on these incidents.

3.8.4.1 Barriers

Resistance to change and concerns about hydrogen safety comprise the overarching challenge for the Education program element. The following section outlines barriers to implementing the education activities intended to address the challenge and meet program goals and objectives.

- A. Lack of Awareness.** Interest in hydrogen and fuel cell technology is increasing, but there remains a general lack of awareness of hydrogen as an energy alternative. Moreover, although world events have drawn new attention to national energy security issues, there is little consensus about the severity of today's environmental problems or linkages to fuel choice. With little awareness, understanding, or recognition of these issues, there is little impetus for change, and target audiences are less inclined to embrace new technology.
- B. Lack of Demonstrations or Examples of Real World Use.** Hands-on and personal experience greatly enhances understanding and comfort with using any new technology. Although the number of hydrogen and fuel cell demonstration projects is slowly growing, currently there are only a few real-world examples to which educators can point. The absence of installations and demonstrations also results in a lack of success stories and case studies to supplement educational materials and encourage early adopters.

C. Institutional Barriers and Access to Audiences. Audience information needs can be well researched and educational materials or training workshops can be well developed, but they must reach their intended audiences to be effective. Institutional barriers can complicate or inhibit access to target audiences. Moreover, identifying the right organizations, as well as a champion within each organization to embrace hydrogen and fuel cell technologies, can be challenging.

D. Regional Differences. Educational needs will vary by audience, but they may also vary regionally. What applies to one state, county, city, or district, may not apply to another. Serving the education needs of a single target audience may therefore require multiple approaches tailored to serve the needs of various regions. This strains resources and can complicate activities developed at the national level.